Oceanic LES Simulations to Interpret and Synthesize Turbulence Measurements Obtained During CBLAST-Low

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LONG-TERM GOALS

To understand the effects of upper-ocean turbulent processes on air-sea interaction and obtain improved parameterization of these processes for use in coastal and large-scale ocean models.

OBJECTIVES

This proposal has two primary objectives: (1) to improve understanding of air-sea interaction in fetch-limited shallow seas; (2) interpret observational data collected during CBLAST-Low.

APPROACH

Because of limited wind fetch and shallow water depth, air-sea interaction in coastal oceans is very different from that in the open ocean. Surface waves in coastal oceans often have a sea state far from the fully-developed sea. As shown in recent observations (Donelan *et al.*, 1993; Garrett, 1997), drag coefficient is a strong function of wave age. At the same wind speed, the air-sea momentum flux in growing seas may be significantly larger than that in fully-developed seas. Wave spectrum in growing seas is narrowly peaked so that the Stokes drift current is different. These differences in wind stress and wave field can cause dramatic changes in turbulence characteristics in the ocean surface layer. The Air-Sea Interaction Tower (ASIT) constructed during the CBLAST program provides an ideal platform to observe and monitor air-sea interaction processes in the coastal ocean. Our modeling work is intended to facilitate the interpretations of the CBLAST measurements and improve our understanding of air-sea interaction in fetch-limited shallow seas.

Surface forcing conditions during CBLAST-Low experiment varied from negligible wind stress and strong thermal forcing to medium wind speeds where wave breaking and Langmuir circulations are expected to play a role in air-sea exchange processes (Plueddemann, 2004). The majority of winds were from the SW quadrant at 3-7 m/s, whereas the weakest winds were from the SE. The strongest winds were from the NW, but these events were short lived compared to those from the SW. Varying wind directions relative to Martha's Vineyard create a complex wave field at the observational site, which may include growing, short-fetch wind waves and decaying wind waves along with persistent swell from the south. To interpret the observational data collected under these complex wind and wave conditions, we have identified a few "key" scenarios/events and conducted simulation studies using the LES model. They include (1) steady wind and growing/decaying waves; (2) steady wind and swells;

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(3) doubling or halving of wind speed and steady waves; (4) misaligned wind and wave directions. These scenario analyses will provide a solid foundation for interpreting hindcast simulations of the CBLAST-Low experiment as the observational data become available for comparison.

WORK COMPLETED

We have conducted LES simulations of the scenarios or events identified from the analysis of CBLAT-Low data. I visited CBLAST field investigators at WHOI and discussed ways for conducting the model-data comparison. We have also analyzed LES results on the penetration of Langmuir and shear turbulence into stratified fluids and developed parameterization schemes for use in mixed layer models.

RESULTS

Analysis of the CBLAST-Low data showed that the coastal ocean is often subject to variable wind and wave forcing. We have run the LES model to explore these time-dependent wind-mixing events, including (1) steady wind and growing/decaying waves and (2) doubling or halving of wind speed and steady waves. The following provides a summary of the model results.

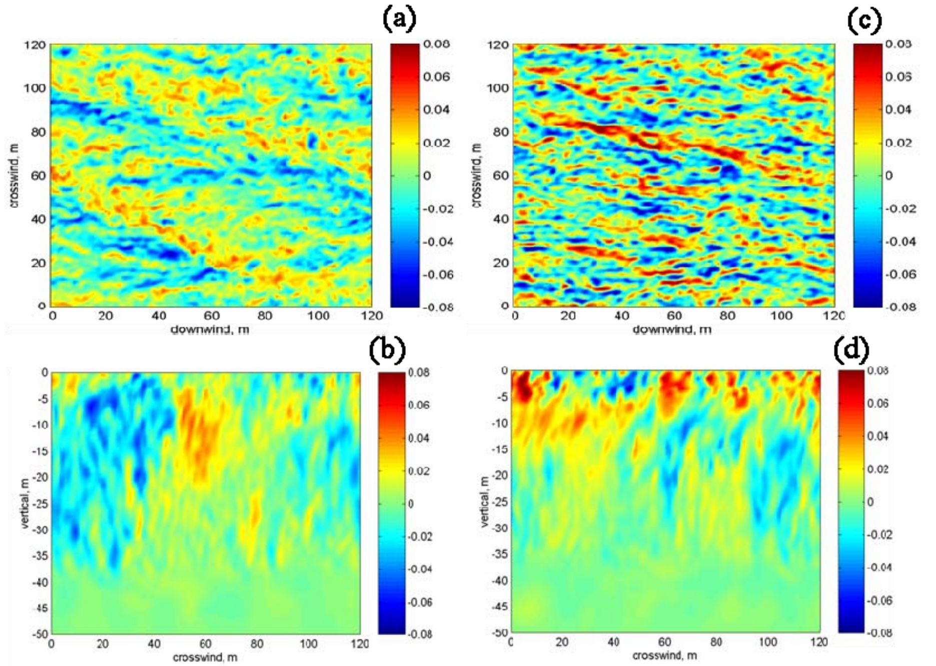

Figure 1. Near-surface (3 m depth) distribution of vertical velocity before (a) and 3 hours (b) after the increase in wave height. Distribution of vertical velocity in a crosswind vertical section before (a) and 3 hours after the increase in wave height. Wind speed is kept constant during this numerical experiment.

In the first set of numerical experiments, we examine the effects of changing wave field on the turbulent dynamics in the upper ocean. Initially, the model is forced by a wind stress of 0.16 Nm^{-2} (wind speed of 10 ms^{-1}), a wave field with the wave height of 2 m and wavelength of 60 m. However, the wave amplitude increases from 2 to 4 m between 1200 and 1300 hour while the wind speed stays the same. Figure 1 shows a comparison of the near-surface and cross-wind distributions of vertical velocity at two times: one at 1200 hour (before the increase in wave height) and 1500 hour (3 hour after the increase in wave height). After the steady forcing of 12 hours, the turbulence field in the upper ocean is dominated by large eddies which nearly occupy the whole mixed layer. The convergence lines as shown by strong downwelling (blue) velocity (Fig. 1a) organize into parallel streaks which are aligned at an angle (about 30 deg to the right) to the wind direction. In the vertical cross section, upwelling (positive vertical velocity) and downwelling (negative vertical velocity) plumes reach to the base of the surface mixed layer (40 m depth) (Fig. 1b).

After the increase in wave height, many new eddies are generated and replace the previous quasi-equilibrium large eddies, as shown in Fig. 1c. These eddies are highly energetic as evidenced by the large velocity magnitude. However, the scale of turbulent eddies appear to have decreased and the convergence lines align more closely with the wind direction. In the vertical section, intense downwelling and upwelling plumes appear in the upper part (down to 10 m) of the mixed layer. Turbulent eddies in the mid and lower part of the mixed layer remained energetic as before. Results shown in Fig. 1 demonstrate that the growth of the wave field substantially reinvigorates Langmuir turbulence in the ocean mixed layer.

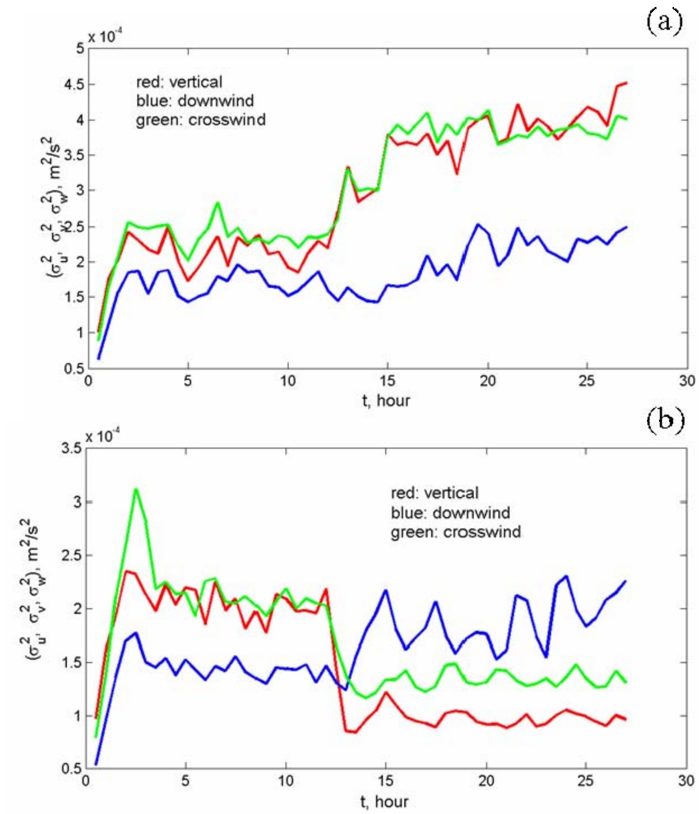

Figure 2. Time series of depth-averaged turbulence intensities (vertical-red, blue-downwind, green-crosswind) for two LES runs: (a) steady wind but a doubling of wave height; (b) steady wind but a 50% reduction in wave height over one-hour period between 12 and 13 hours.

Following Li et al. (2005), we calculate three components of turbulence intensities averaged over the mixed layer. Their magnitudes indicate the strength of turbulence eddies while the ordering of the turbulence intensities serve to distinguish the characteristics of these eddies. As shown in Fig. 2a, the increase in wave height caused the vertical and crosswind turbulence intensities to double, increasing from 2 to 4 m^2s^{-2}. In the regime diagram of Li et al. (2005), a doubling of wave height causes a 50% reduction in turbulent Langmuir number, thus pushing the turbulence further into the wave-dominated Langmuir turbulence regime. It is interesting but not surprisingly to note that the turbulence intensity in the downwind direction stayed almost flat. For comparison, we conduct another LES run in which the wave height reduces from 2 to 1 m while the wind speed is fixed at 10 ms^{-1}. We plot the time series of the turbulence intensities from the second LES run in Fig. 2b. The reduction in the wave height causes a large reduction (more than a factor of 2) in the vertical component of turbulence intensity and smaller reduction in the cross-wind turbulence intensity. In contrast, the downwind turbulence intensity jumps by about 50%. After the wave height decrease from 2 to 1 m, the turbulence intensity has an ordering of downwind > crosswind > vertical component, as expected for a shear-driven turbulence (Li et al., 2005). Therefore, the reduction in wave height causes the turbulence field in the upper ocean to switch from Langmuir to shear turbulence.

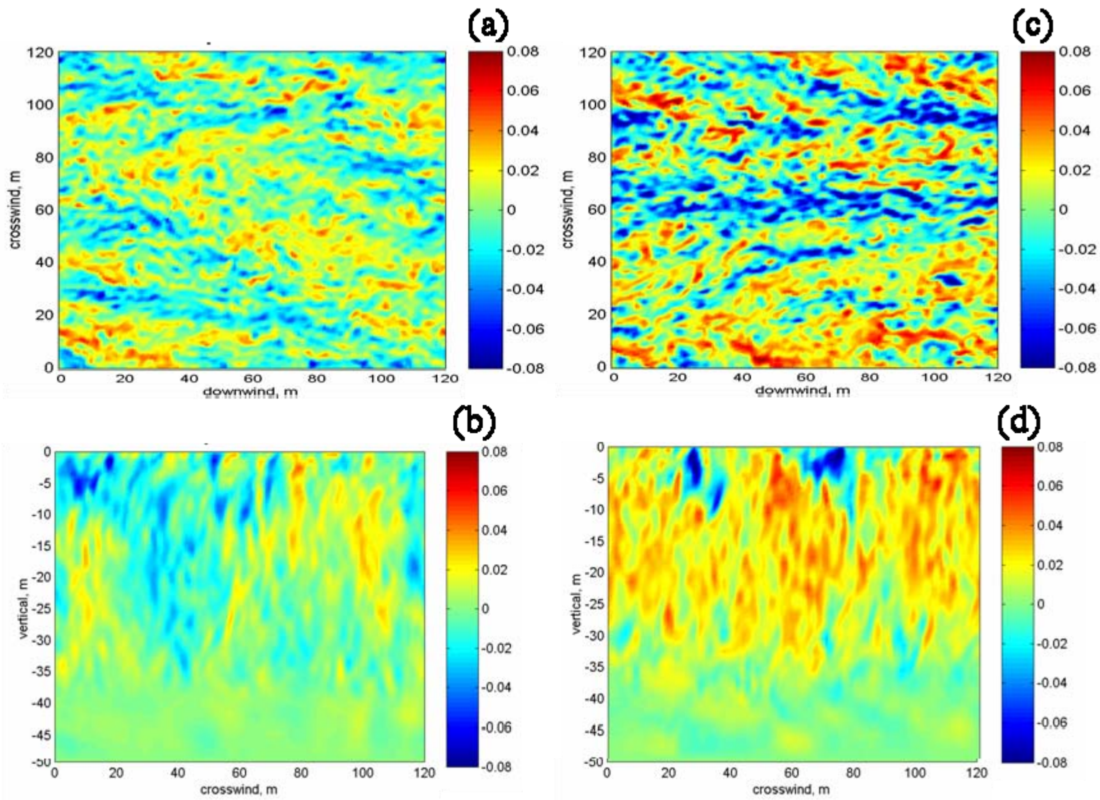

Figure 3. Near-surface (3 m depth) distributions of vertical velocity before (a) and 3 hours (b) after the increase in wind speed. Distributions of vertical velocity in a cross-wind vertical section before (a) and 3 hours after the increase in wind speed. Wave field is fixed to be the same.

In the second set of numerical experiments, we fix the wave field but increase the wind speed from 10 to 20 ms^{-1}. Turbulence field in Figs. 3a and 3b shows the alternating upwelling and downwelling plumes typical of Langmuir turbulence. After the increase in wind speed, turbulence field becomes much stronger, as expected. However, the structure of the turbulent eddies appear to be different. Many small eddies appear in Fig. 3c and 3d, but not all of them are aligned in the wind direction.

This change in turbulence structure can be understood when we examine the time series of the depth-averaged turbulence intensities, as shown in Fig. 4a. Before the increase in wind speed, the turbulence intensity has the ordering of vertical = crosswind > downwind component, which is a distinct characteristic of Langmuir turbulence (see Li et al., 2005). However, after the doubling of the wind speed, the turbulence intensity has the ordering of downwind > crosswind > vertical component, which is a characteristic of shear-driven turbulence. Therefore, the turbulence field in the upper ocean switches from Langmuir to shear turbulence after the doubling of the wind speed. This change in the ordering of three components of turbulence intensities is consistent with the apparent changes in the structure of turbulent eddies as shown in Fig. 3. For comparison, we conduct another LES run in which the wind speed decreases from 10 to 5 ms^{-1}. Figure 4b shows that all three components of turbulence intensities decrease by a factor of 3 while their ordering remains the same. Turbulence field in the upper ocean remains to be Langmuir turbulence but its strength is much reduced after the decrease in wind speed.

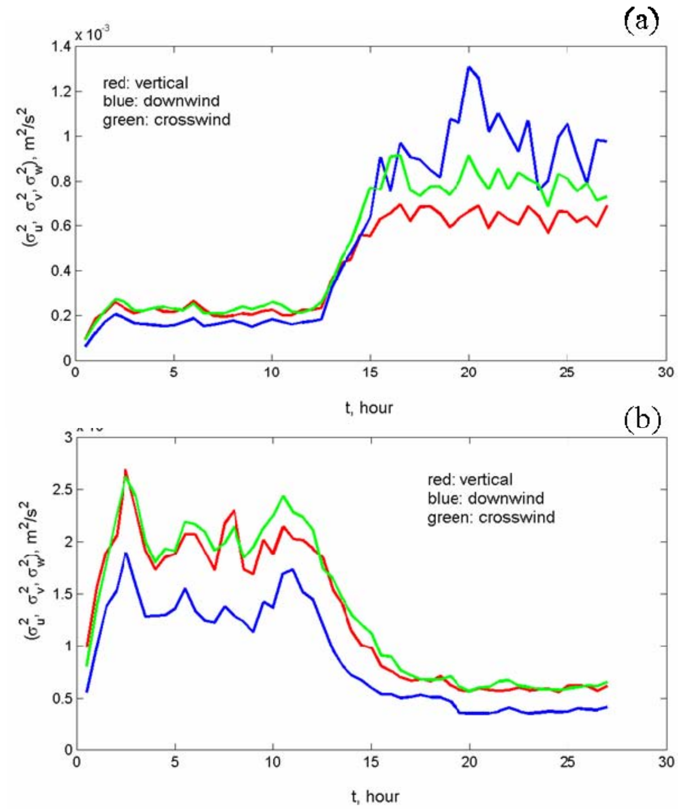

Figure 4. Time series of depth-averaged turbulence intensities (vertical-red, blue-downwind, green-crosswind) for two LES runs: (a) steady wave but a doubling of wind speed; (b) steady wave but a 50% reduction in wind speed over one-hour period between 12 and 13 hours.

In summary, we have conducted a series of LES numerical experiments to explore how changing wave or wind field affect the turbulent eddies in the upper ocean. We found that a reduction in the wave height under constant wind speed causes the switch from Langmuir to shear turbulence. The switch from Langmuir to shear turbulence may also be generated by an increase in the wind speed if the wave field stays the same. For the fully-developed seas in the open ocean, Li et al. (2005) showed that the turbulence in the upper ocean is dominated by Langmuir turbulence. The new numerical experiments as reported here suggest that upper-ocean turbulence in fetch-limited coastal oceans can make a transition from Langmuir to shear turbulence under changing sea state conditions.

IMPACT/APPLICATIONS

Our modeling investigations into the upper-ocean turbulence dynamics will contribute to a better understanding of air-sea interaction and help interpret CLBAST field observations.

RELATED PROJECTS

We collaborate with John Trowbridge, Al Plueddeman, Tim Stanton, Bob Weller and Jim Edson on interpreting data from CBLAST experiments

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